Photon-counting detectors for space-based laser receivers

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ABSTRACT

Photon-counting detectors are required for numerous NASA future space-based laser receivers including science instruments and free-space optical communication terminals. Silicon avalanche photodiode (APD) single photon counting modules (SPCMs) are used in the Geoscience Laser Altimeter System (GLAS) on Ice, Cloud, and land Elevation Satellite (ICESat) launched in 2003, currently in orbit measuring the Earth surface elevation and atmosphere backscattering. To measure cloud and aerosol backscattering, the SPCMs detect the GLAS laser light at 532-nm wavelength, with quantum efficiencies of 60 to 70% and maximum count rates greater than 13 million per second. The performance of the SPCMs has been monitored since ICESat launch on January 12, 2003. There has been no measurable change in the quantum efficiency, linearity or after-pulsing. The detector dark counts rates monitored while the spacecraft was in the dark side of the Earth have increased linearly at about 60 counts/s per day due to space radiation damage. As the ICESat mission nears completion, we have proposed ground-to-space optical and quantum communication experiments to utilize the on-orbit 1-meter optical receiver telescope with multiple SPCMs in the focal plane. NASA is preparing a follow-on mission to ICESat, called ICESat-2, with a launch date of late 2014. The major candidate photon-counting detectors under evaluation for ICESat-2 include 532 nm and 1064 nm wavelength-sensitive photomultiplier tubes and Geiger-mode avalanche photodiode arrays. Key specifications are high maximum count rate, detection efficiency, photon number resolution, radiation tolerance, power consumption, operating temperature and reliability. Future NASA science instruments and free-space laser communication terminals share a number of these requirements.

Keywords: Photon-counting, detectors, satellite, lasers, avalanche-photodiodes, photomultipliers, optical communication, entanglement

1. INTRODUCTION

Minimizing space-based resources (size, weight, power and cost) is an important goal for all NASA science missions. Recently, high-efficiency lasers and detectors have become available that may allow a new-class of space-based lidars. Unlike first generation lidars that use low repetition rate (tens of Hertz) large energy pulsed lasers (tens of mJ), this new class of lidars will use high-repetition-rate (kilo-Hertz) low-pulse-energy lasers (tenths of mJ). With low energy lasers, the large return signal dynamic range due to rapid change of the earth atmosphere (e.g. clouds) and ground surface scattering/reflectivity is a major challenge. To date, space-based lidars use a linear-mode (analog) avalanche photodiode[1] or analog photomultiplier[2] in conjunction with an automatic-gain-control circuit to cover the large return signal dynamic range. However, the sensitivity of the present analog detectors is limited. The receiver performance can be improved by one to two orders of magnitude by using single-photon-sensitive detectors. Photomultipliers and avalanche photodiodes are the primary candidates.

Photomultiplier tubes have been used in space as single-photon-counting detectors mostly on astronomy missions (e.g. PAMELA[3]). Single photon avalanche photodiodes (SPAD) have also been used in several space missions[4,5]. Si APD SPCMs are currently used on the ICESat/GLAS instrument to detect laser light backscattered from the atmosphere[6,7]. There are two major limitations, namely, 1) each Si APD can detect only one photon at a time with a fifty-nanosecond dead time and 2) each Si APD has a nonlinear saturation effect at high photon count rates. This makes it difficult to cover a large return signal dynamic range with a single APD, especially with signal returns from the ground surface under clear sky conditions. Some circuitry has been added to certain Geiger–mode APDs detectors to help estimate the number of photons in the pulse and correct for the nonlinear effect, but it can only do so for a fixed input laser pulse width[4]. One technique to mitigate this constraint is to reduce the laser pulse energy but increase the laser pulse rate so

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that the receiver will not saturate on any single laser pulse and to achieve the required SNR by averaging the results of many laser pulse measurements[8,9]. The disadvantage of this technique is higher receiver noise due to the increased receiver integration time. The receiver is also more complicated since it has to record all the signal and noise photons at the required timing accuracy before filtering out signal from noise.

The dynamic range issue can be solved with an array of Geiger-mode APDs to provide photon number when the outputs are added at the receiver. This technique was used and demonstrated by the SPCM array on GLAS. Recently, a dramatic demonstration of this technique was made for an integrated APD array[10]. The same concept is now used in integrated APD micro-array commercial products (a.k.a. solid state photomultipliers) made by Sensl[11], Hamamatsu[12], and Amplification Technologies[13]. We are currently evaluating these devices. Our requirement is not only to resolve the photon number in a pulse, but also the arrival time of each photon to retrieve the temporal profile of the received laser pulse for an unbiased time-of-flight measurement.

Another type of photodetector that can resolve single to multiple photons in a pulse is the hybrid photomultiplier tube; also know as the intensified photodiode. These devices use electron bombardment for the first-stage gain resulting in a very low excess noise factor (1.04). Hamamatsu offers a commercial device that resolves the photon number in the visible region[14]. Intevac offers a similar device for use in the near infrared[15,16].

2. SPCMS ON ICESAT/GLAS

Si APD SPCMs (Figure **1**) were used on ICESat/GLAS for cloud and aerosol backscattering measurements at 532 nm wavelength. Because of the high signal dynamic range, the received optical signal was equally split into eight SPCMs. Unfortunately, four of the SPCMs malfunctioned during ground testing and a decision was made not to replace them, but to use the remaining four SPCMs for the on-orbit measurements. These four SPCMs have operated flawlessly from ICESat launch in 2003 to this date. Figure 2 shows the eight SPCMs mounted on the beam splitter assembly prior to integration to the GLAS instrument. A comprehensive summary of the SPCM performance is given by Sun[6].

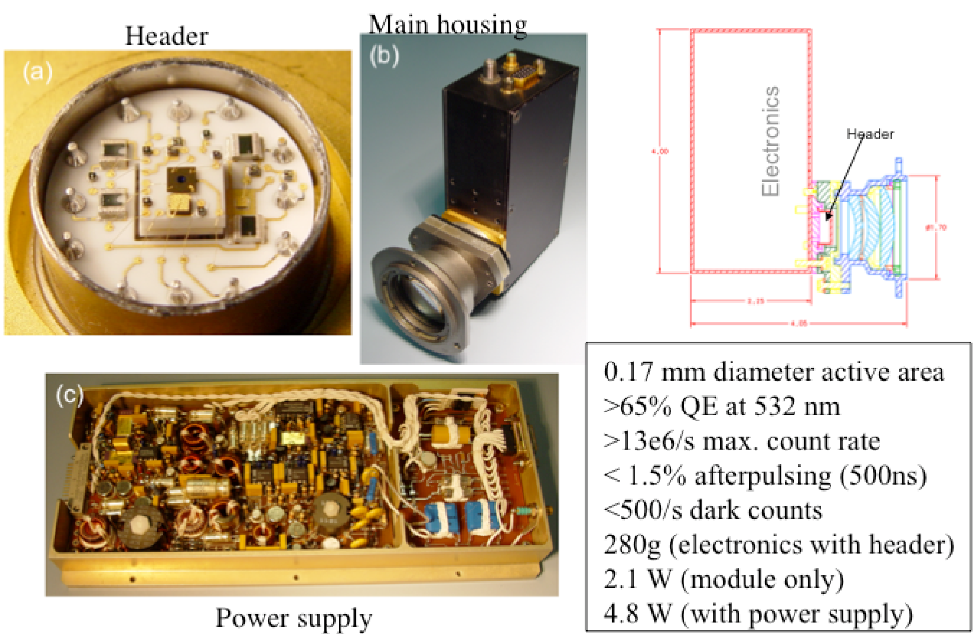

Figure 1. Single Photon Counting Module (SPCM) used in ICESat/GLAS.

Figure 3 shows the SPCM response to the sunlit Earth before the laser pulse enters the Earth atmosphere. The peak photon counts observed near local noontime gives a measurement of the SPCM photon-counting efficiency after correcting for solar angle effects. The observed maximum count rate corresponded to backscattered solar light from a 100% reflectance cloud deck. This shows that the SPCM photon-counting efficiency has remained nearly constant over the seven-year deployment in space.

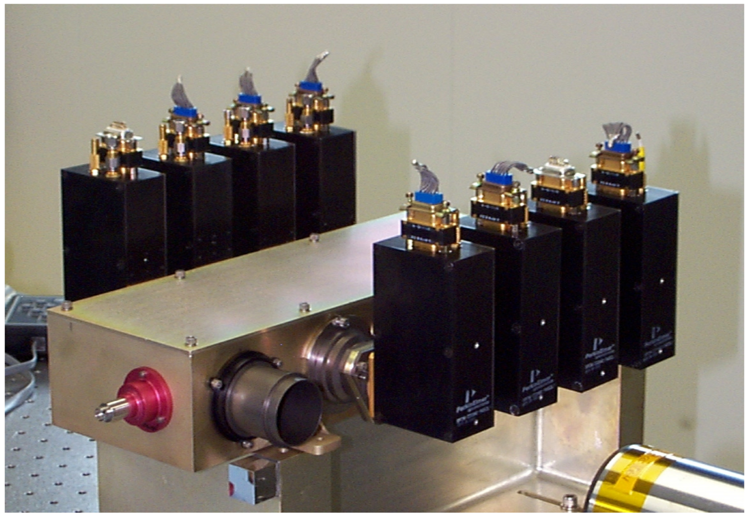

Figure 2. Eight Single Photon Counting Modules on the ICESat1/GLAS satellite shown in pre-integration testing.

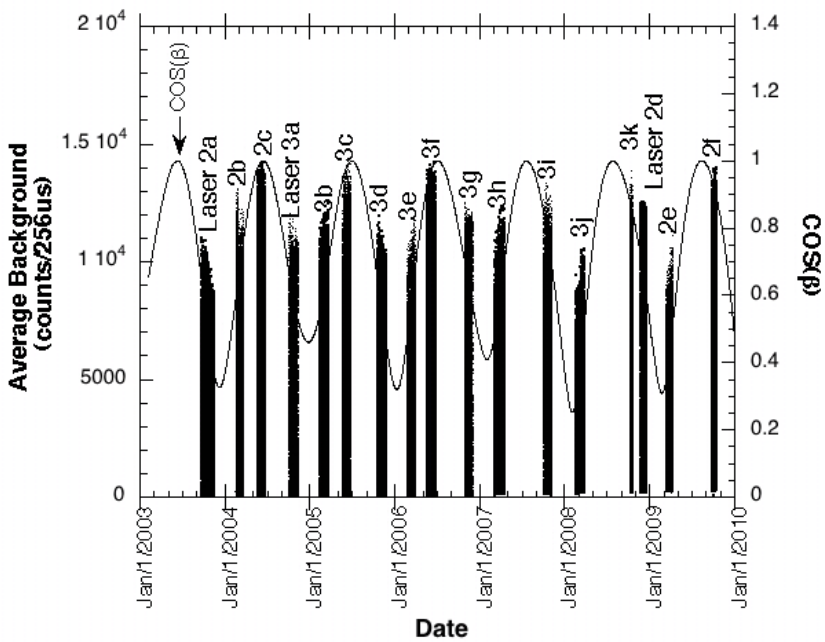

Figure 3. Sum of the four SPCM outputs in response to the sunlit Earth over the entire ICESat mission duration to date, along with the sun angle effect (cos(β) with the angle β between the sun ray and the ICESat orbit plane).

Figure 4 shows the SPCM output over the dark side of the Earth providing a measurement of the SPCM dark count rate and radiation damage over time and at different temperature. These SPCMs were not powered on during the first 9 months of the mission, powered on three times a year and 30-40 days each time till early 2007, and twice a year afterwards. The radiation damage to these Si APDs was apparent, though slightly below the predicted rate, but it did not have any major effect on the atmospheric backscattering measurements. The rate of radiation damage was the smallest during the first 9 months when the ambient temperature was the highest. The space-radiation damage induced dark-count rate increase then became about 60 counts/s per day per device from late 2003 to mid of 2007, and nearly 200 counts/s per day after that when the average instrument temperature became lower. To our knowledge, these are the first in orbit observations of Si APD radiation damage in a near Earth orbit over such a long period of time. The results may be scaled for other type of Si devices in a similar operating environment. We are planning to raise the SPCM temperature for a few days at the end of the mission and measure the dark count rates again to observe any possible annealing effects.

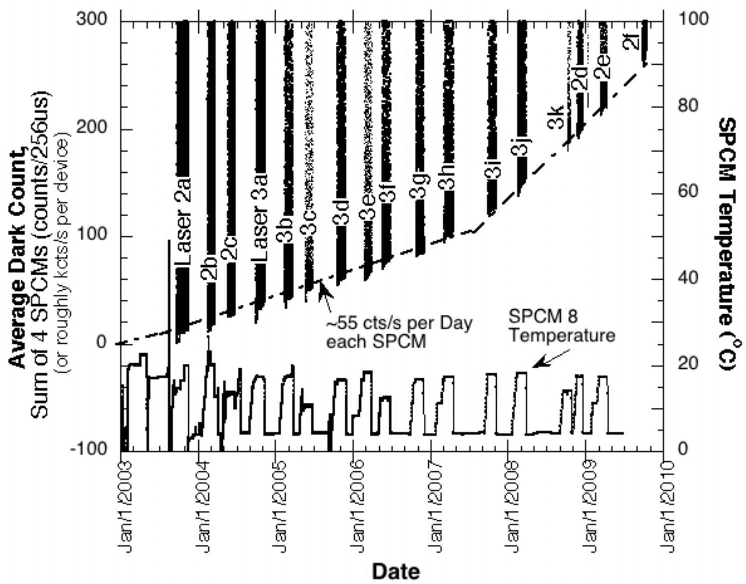

Figure 4. Increase in dark counts of ICESat SPCMs on orbit since January 2003 due to space radiation.

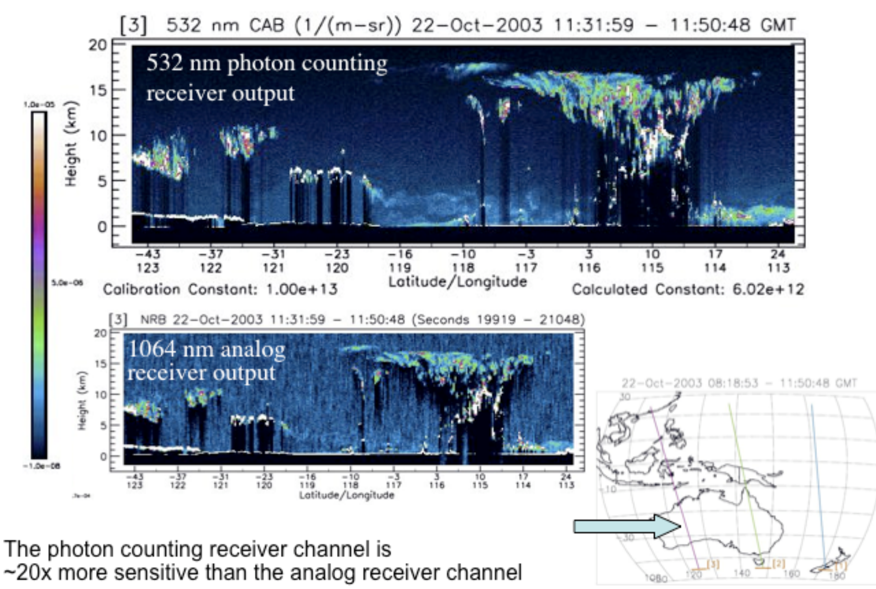

Figure 5. Sample ICESat/GLAS atmosphere backscattering measurements by the SPCMs and the linear-mode 1064 nm silicon APD.

Figure 5 shows atmospheric backscattering measurements[17] using these SPCM detectors, in comparison with exactly the same on-orbit measurements, using the analog Si APD detector. This shows that the single photon detectors are 20 to 50 times more sensitive than the analog detector.

3. CANDIDATE PHOTON-COUNTING DETECTORS FOR ICESat-2/ATLAS

ICESat2/ATLAS (Ice, Cloud and land Elevation Satellite 2/Advanced Topographic Laser Altimeter System) is planned for launch in December of 2014. ICESat2/ATLAS is a follow-on mission to the ICESat/GLAS mission whose primary purpose is to monitor the Earth polar ice sheets height and volume. Unlike ICESat/GLAS, ICESat2/ATLAS will use photon-counting detectors and a high-repetition-rate (10 kHz) laser to perform the laser altimetry measurements. Only a single wavelength will be used. Near-infrared wavelength operation is preferred because of the reduced solar background, double the number of photons for a given laser energy, lack of a complex doubling requirement and corresponding higher electrical efficiency and reduced thermal load. However, both 532 nm and 1064 nm are under consideration as we further develop robust, reliable, capable detectors usable at 1064 nm. For ICESat 2, major candidate photon-counting detectors under evaluation include 532 nm and 1064 nm wavelength-sensitive photomultiplier tubes and Geiger-mode avalanche photodiode arrays. Key specifications are short dead time, maximum continuous count rate, detection efficiency, photon number resolution, timing jitter, radiation tolerance, power consumption, operating temperature and reliability. Table 1 lists candidate photon-counting detector technologies for use at 532 nm wavelength. Table 2 lists candidate photon-counting detector technologies for use at 1064 nm wavelength.

Table 1. Photon-counting detector requirements, parameters and technology candidates for ICESat2/ATLAS at 532 nm wavelength. *(TRL = Technology Readiness Level)*

Parameter	**Requirements**	**GLAS SPCM-Perkin Elmer (16 per channel)**	**Hamamatsu PMT R5900**	**Hamamatsu HPMT H10777-40**	**Silicon APD microarray (8x8) (4 per channel)**
TRL/Space flight heritage	TRL 6 by Preliminary Design Review	TRL 9 on ICESat/GLAS	TRL 9 on PAMELA	TRL 4	TRL 4
Photon Detection Efficiency	20%	65%	15%	40%	20%
Maximum count rate (MCPS)	300	200	200 (to be tested)	300 (to be tested)	30
Timing jitter (ps, FWHM)	230	300	300 (FWHM data sheet)	90	60
Multiple photon resolution	5	16 (multiple detector)	To be measured	Yes	Yes (multiple detector)
Dark Count (kHz)	30	500	< 100 counts per second	<30	4
Lifetime (years) (at a solar background of 10^7 cps)	5	5	> 5	4.7	> 5
Diameter (μm)	200	170	1600	3000	800

Table 2. Photon-counting detector requirements, parameters and technology candidates for ICESat2/ATLAS at 1064 nm wavelength.

Parameter	Requirements	IPD	GLAS SPCM -Perkin Elmer (8 per channel)	InGaAs APD microarray (16x16 with ROIC)
TRL/Space flight heritage	TRL 6 by PDR	TRL4	TRL 9 on ICESat/GLAS	TRL 3
Detection Efficiency	10%	20%	5%	15%
Maximum count rate (MCPS)	300	>200	100	>100 (to be verified)
Timing jitter (ps, FWHM)	230	150	300	200
Multiple photon resolution	5	Yes	8	Yes
Dark Counts (kHz)	15	60	20	<10
Lifetime (year) (under solar background of 5x10^6 cps)	5	4	5	no data, Solid state device, radiation issues
Diameter (μm)	200	1000	170	50

4. IDEAS FOR POSSIBLE GROUND-TO-SPACE EXPERIMENTS USING ICESAT/GLAS PHOTON-COUNTING DETECTORS

4.1 Classical optical communication experiment

The ICESat/GLAS satellite instrument has a 1064 nm receiver with a linear-mode near-infrared enhanced (37% quantum efficiency at 1064 nm) silicon avalanche photodiode[1] and four operational high-efficiency (65% detection efficiency at 532 nm) photo-counting detectors that reside in the focal plane of its one-meter optical receiver telescope. There is an 800 pm 1064 nm interference filter[18] in the infrared receiver and 350 pm interference filter cascaded with a 28 pm etalon[19] filter in the 532 nm receiver. We propose to conduct ground-to-space classical optical communication experiments at 532 nm and 1064 nm. The 1064 nm and 532 nm receiver-timing resolutions are 150 ps and 500 ns respectively. A series of ground-to-space classical optical communication experiments at 532 nm and 1064 nm is currently under consideration at NASA-GSFC that would use our present optical communication test bed[20] hardware.

4.2 Quantum photon-entanglement experiment

Two-photon interference effects lead to the starkest contrasts between classical and quantum theory. They can display the non-local realism of quantum mechanics through tests of Bell inequalities. In fact, the Bell-type entanglement needed for quantum information applications is most readily observed in two-photon systems. The GLAS instrument with its SPCMs may present an opportunity to test long-distance quantum entanglement. We are examining some possible ideas to test long-distance quantum entanglement using these detectors after the completion of the GLAS mission. Unfortunately, due to the lack of any polarizer in the receiver path, we cannot perform the typical CHSH Bell test experiments as first done by Aspect[21,22]. Our initial idea is a modified Franson interferometer[23,24] to test the time-time correlations of entangled photons. The objective of an experiment would be to provide further experimental evidence of the non-local quantum behavior. These experiments rely on photon-coincidence-rate detection of the unique fourth-order quantum interference term. We refer the reader to an excellent overview article by Mandel[25].

Two correlated photons incident upon two separate interferometers can produce a coincidence rate that depends on the sum of the phases of the interferometers - nonlocally (i.e. over a large distance - 600 km in our proposed experiment). Figure **6** shows the standard two-photon Franson interferometer experiment.

Figure 6. Two-photon Franson interferometer experiment.

Our idea is shown in Figure 7. It is essentially the same as the Franson experiment using two-photons with two separate interferometers separated by a large distance. We generate time-entangled photon pairs at 532nm and 1064 nm. In the same approach as the Franson experiment, we use one Mach-Zehnder interferometer for the 1064 nm photons with a user selectable path (phase) delay on the ground and a photon-counting detector. However, since we do not have access to a Mach-Zehnder interferometer deployed in Earth orbit, for the second (distant) interferometer, we suggest the use of a wavefront splitting interferometer. We propose to split the beams on the ground, but with almost common paths to minimize the effects of optics imperfections and atmospheric turbulence. The two beam's angular separation is much less than individual beam divergence. In this case, the beams combine at the ICESat/GLAS satellite receiver telescope with no path information. One arm of the interferometer is much longer than the other. The path length difference is set to be much longer than the light source coherence length so that no first-order interference fringes can be observed.

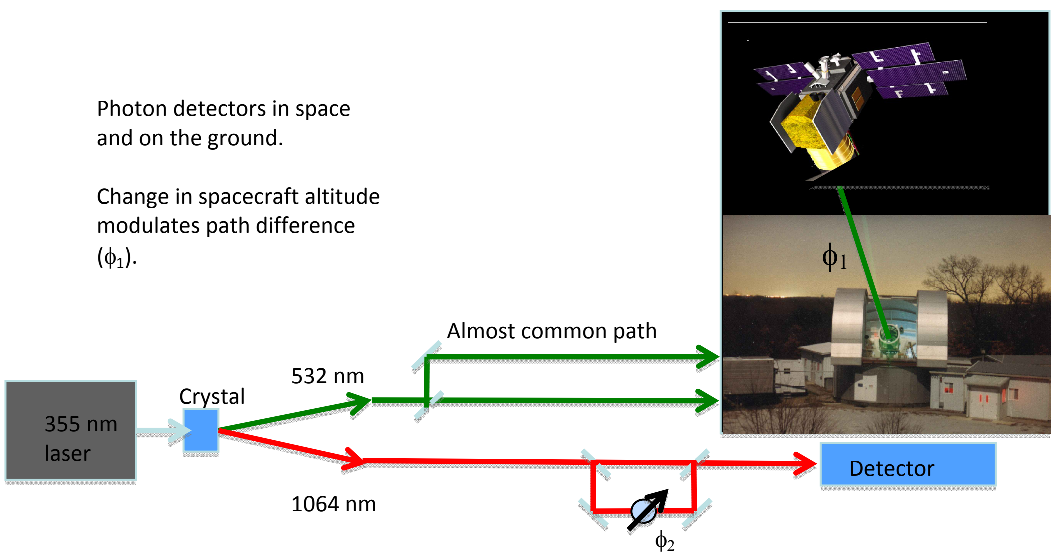

Figure 7. Possible ground-to-space Franson interferometer experiment using the ICESat GLAS instrument photon-counting detectors in low Earth orbit.

The difficulties in realizing these experiments include the short time span in which a line-of-sight can be established between the orbiting satellite and the ground station. The ICESat satellite is capable of open-loop pointing (yaw and pitch) to a location on the ground (i.e. "dwell") by maneuvering the spacecraft as it passes on each track on its 90-minute orbit. An estimated time of contact per orbiting track is on the order of few seconds. On the previous and subsequent tracks (possible two more) over the same location, the satellite may also be maneuvered to point to the ground terminal to increase the observation time. This will ideally provide a few tens of seconds of total line-of-sight contact. An estimated 1200 entangled photons over the contact time duration is expected to be necessary to demonstrate this experiment.[26] A high photon-pair generation rate entangled source is required to establish a quantum communication link to build up the statistics necessary to perform this experiment. The effects of atmospheric turbulence, spacecraft motion Doppler-shift, the GLAS receiver timing resolution and many other considerations are being analyzed.

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